Exoskeleton Application to Military Manual Handling Tasks

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1. Abstract

Objective: The aim of this review was to determine how exoskeletons could assist Australian Defence Force personnel with manual handling tasks.

Background: Musculoskeletal injuries due to manual handling are physically damaging to personnel and financially costly to the Australian Defence Force. Exoskeletons may minimise injury risk by supporting, augmenting and/or amplifying the user's physical abilities. Exoskeletons are therefore of interest for determining how they could support the unique needs of military manual handling personnel.

Method: Industrial and military exoskeleton studies from 1990 - 2019 were identified in literature. This included 67 unique exoskeletons, for which Information about their current state of development was tabulated.

Results: Exoskeleton support of manual handling tasks is largely through squat/ deadlift (lower limb) systems (64%), with the proposed use case for these being load carrying (42%) and 78% of exoskeletons being active. Human-exoskeleton analysis was the most prevalent form of evaluation (68%) with reported reductions in back muscle activation between 15% and 54%.

Conclusion: The high frequency of citations to exoskeletons targeting load carrying reflects the need for devices that can support manual handling workers. Exoskeleton evaluation procedures varied across studies making comparisons difficult. The unique considerations for military applications, such as heavy external loads and load asymmetry, suggest that significant adaptation to current technology or customised military-specific devices would be required for the introduction of exoskeletons into a military setting.

Application: Exoskeletons in the literature and their potential to be adapted for application to military manual handling tasks is presented.

Keywords: Exosuits, Wearable robotics, Bio-mechatronics, Biomechanics, Assistive technologies, Manual materials, Industrial.

Précis: A narrative review identifying current exoskeleton research for assistance in manual handling tasks and determining how these exoskeletons could assist military personnel. Information about the exoskeletons state of development was tabulated, the results of these details are presented and the application of the exoskeletons to military and industry was discussed.

2. Introduction

In Australia 43% of serious injuries in the workplace are due to traumatic joint, ligament, muscle and tendon injuries, at an annual cost of AU$19.5 billion for treatment, over-employment, overtime, retraining and investigation (Safe Work Australia, 2019). Forty-five percent of serious workplace injuries were due to manual handling, a term used to describe tasks in which human force is used to manoeuvre an object’s position (Carstairs, Ham, Savage, Best, Beck, & Billing, 2018). Manual handling injuries are of particular concern in physically demanding Defence Force occupations. Most manual handling injuries are associated with the upper and lower limbs (37%) and the back/trunk (38%) (Safe Work Australia, 2019). Internationally, over 40% of workers in the European Union experience lower back, neck or shoulder pain caused by manual handling related workloads and repetitive movements (de Looze, Bosch, Krause, Stadler, & O’Sullivan, 2016).

Musculoskeletal injuries make up 20% of the most common disorders supported for Australian military personnel returning from active service. The Australian Government's Department of Veteran Affairs found that 7934 veterans (13%) from the East Timor, Solomon Islands, Afghanistan, Iraq and Vietnam conflicts receive support for lumbar spondylosis (Australian Government, 2017), a condition causing pain and restricted motion in the lower back attributed to overuse (Middleton & Fish, 2009). Also, common in military personnel were acute sprain and strain (4%), intervertebral disc prolapse (2%) and thoracic spondylosis (1%) (Australian Government, 2017). These musculoskeletal disorders could be caused by manual handling tasks that involve movements that contribute to an increased risk of musculoskeletal injuries. Exploring how exoskeletons can support the body during manual handling tasks may help in reducing the risk of musculoskeletal injuries.

Factors contributing to manual handling injuries include hyperflexion or hyperextension of the lumbar spine caused by external torques, internal torsional forces, fatigue due to increased total work (Neumann, 2009) and increased spinal flexion when performing lifting tasks from the floor (S. A. Ferguson, Marras, Burr, Davis, & Gupta, 2004; Ngo, Yazdani, Carlan, & Wells, 2017). Additionally, lifting above an individual's intrinsic capacity can be responsible for injuries (Savage, Best, Carstairs, & Ham, 2012).

A comprehensive analysis of Australian Army personnel categorised 79% of all physically demanding tasks as manual handling (Carstairs et al., 2018) encompassing four movement patterns: vertical lifting (305 tasks), locomotion with load (153 tasks), push/pull (38 tasks) and repetitive striking (30 tasks). These movement patterns were further categorised into ten task-based clusters. While some tasks are unique to military personnel the two most common task-based clusters (lift to platform and lift-carry-lower) are also prevalent in many manual handling industries. Therefore, this review could be extended to the application of exoskeletons in industries whose workers perform these movement patterns.

Exoskeletons are an externally fitted biomechatronic or mechanical system, designed to assist the human user in order to reduce injury risk, amplify natural ability, rehabilitate movements or assist for physical challenges (de Looze et al., 2016; Zaroug, Proud, Lai, Mudie, Billing, & Begg, 2019). Exoskeletons can be categorised by the intended purpose of the system: assistive systems, human amplifiers, rehabilitative systems and haptic interfaces (Gopura, Bandara, Kiguchi, & Mann, 2016). An assistive system provides additional support to workers through joint bracing and control or transmitting forces away from the musculoskeletal system, a human amplifier increases the strength capabilities of the human body beyond their natural ability and rehabilitative systems assist in recovery of limb movement for people with limited function. A haptic interface exoskeleton provides feedback to the user when using tele-operation devices. This review explores assistive systems and human amplifiers for their use in supporting manual handling personnel.

The aim of this review was to analyse the current literature to identify characteristics of industrial exoskeletons that can be useful to military manual handling tasks. We therefore classified the exoskeletons based on (1) which manual handling task does the exoskeleton permit, and (2) what joint does the exoskeleton support.

3. Method

A study of the current exoskeleton literature was performed using Scopus, for articles published between January 1990 and December 2019. The search terms included exoskeleton, wearable robot or robot suit with the additional terms industrial, military, manual handling, material handling, lifting, carrying, pushing, pulling and striking. The included search terms were determined by using the definition of manual handling as set by research into Australian Army tasks (Carstairs et al., 2018).

Original studies were considered eligible if they met the following inclusion criteria: (1) the purpose of the exoskeleton was stated using terms such as industrial, military, manual handling, material handling, lifting, carrying, pushing, pulling or striking; (2) the conceptual design of the exoskeleton was progressed to a physical prototype; (3) the manual handling load was supported anterior to the user; (4) the exoskeleton provided actuation on one primary supporting joint (e.g. knee, hip, spine, shoulder) used to execute lift to platform and/or lift-carry-lower tasks. We excluded any commercially available exoskeleton (see limitation section) that did not have published scientific evidence.

The initial search resulted in 357 studies. The texts were screened, and 284 studies were excluded. In total, 73 studies were included in the review (Figure 1) that resulted in 67 individual exoskeleton systems. Included studies were categorised based on which movement patterns they permit (e.g.

squat/deadlift, shoulder/chest press and isometric arm hold or any combination of these movement patterns) and which joints they provided actuation to.

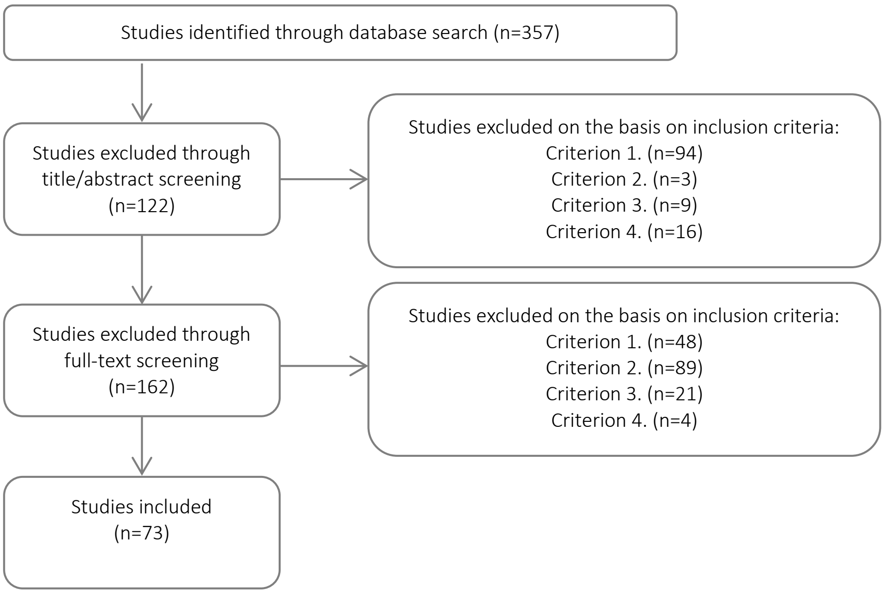

Figure 1 Schematic of the number of studies excluded on the basis on inclusion criteria during the search process. See text for description of criteria.

In order to categorise exoskeletons for their application to military manual handling tasks our focus was on the dominant two task-based clusters, the lift to platform cluster (198 tasks) and the lift-carry-lower cluster (100 tasks) which comprised 56% of army manual handling tasks. There was commonality of the major movement patterns (shoulder/chest-press, squat/deadlift and isometric arm hold movements) and the supporting joints used to execute these tasks (Table 1). Exoskeletons were categorised into the key movement patterns they work on, then sub-categorised into the key supported joints (Table 1). We define the supported joint as the joint upon which the exoskeleton provides actuation. Therefore, an exoskeleton can be designed to assist a segment/joint (i.e. the spine) by providing actuation to – supporting – a joint (i.e. the hip).

Table 1 Key movement patterns and supporting joints for task clusters

	LIFT TO PLATFORM		LIFT-CARRY-LOWER
KEY MOVEMENT PATTERN	Squat /Deadlift	Shoulder/ chest-press	Shoulder/ chest-press & Isometric arm hold
KEY SUPPORTING JOINTS	Knee	Shoulder	Shoulder
	Hip	Spine	Spine
	Spine		

Operational details included device name, purpose, targeted assistance, actuation method, actuators, degrees of freedom (DOF), device weight, control method, sensor system and load capability. The purpose of the exoskeleton was classified based on the principle function/s or the motivation for design. These were defined as: (1) “tool holding”, supporting the weight or reducing the transfer of vibrations from a tool to the user, particularly during overhead work; (2) “injury prevention”, reducing the transfer of external loads to the user’s joint and muscle; (3) “amplification”, typically full body suits taking the entire external load through their structure; and (4) “load carrying”, bearing an external load through the exoskeleton’s structure.

Evaluation details included task analysis, testing performed, test details, sample size, participant details and test results. Task analysis outlined any assessments that were performed prior to the design of the exoskeleton to determine its requirements. Testing performed on the exoskeletons were categorised into the following analyses: (1) “exoskeleton structural design”, analysed for how it moves, the workspace it requires and the forces it is able to withstand/exert; (2) “human-exoskeleton analysis” how it interacts with the user to provide assistance, the forces it applies to the user and how the user’s natural motion can be changed by the addition of the device; (3) “accuracy of the sensor system” analysed for its accuracy, resolution, efficiency, speed and output; and (4) “response characteristics of the control system” how the mechatronic system interacts with the user and can be measured by accuracy, speed, sensitivity and complexity.

4. Results

4.1. Exoskeletons classification

4.1.1. Movement patterns and supported joints

Twenty-four percent of exoskeletons permitted shoulder/chest press and isometric arm hold motions (Table 2), this includes devices that support the elbow and shoulder joints concurrently (n=9) and the shoulder joint only (n=7) (Figure 2). Sixty-four percent of exoskeletons permitted the squat/deadlift movements (Table 3), this includes devices that support the ankle, knee and hip synchronously (n=20), the knee joint only (n=4) and the hip joint only (n=19) (Figure 2), while 12% of exoskeletons permitted major joints for shoulder/chest press, isometric arm hold and squat/deadlift (Figure 2) (e.g. spine (n=5) and full body devices (n=3)) (Table 4).

4.1.2. Purpose

Load carrying was the most common exoskeleton purpose (42%), followed by 22% targeting load carrying and injury prevention (Figure 2). Load carrying included lifting, lowering and/or carrying of external loads. Injury prevention exoskeletons focused on trying to reduce injury risk factors of the lower back while tool holding devices, making up 15% of this review, focused on supporting the shoulder joints through unloading.

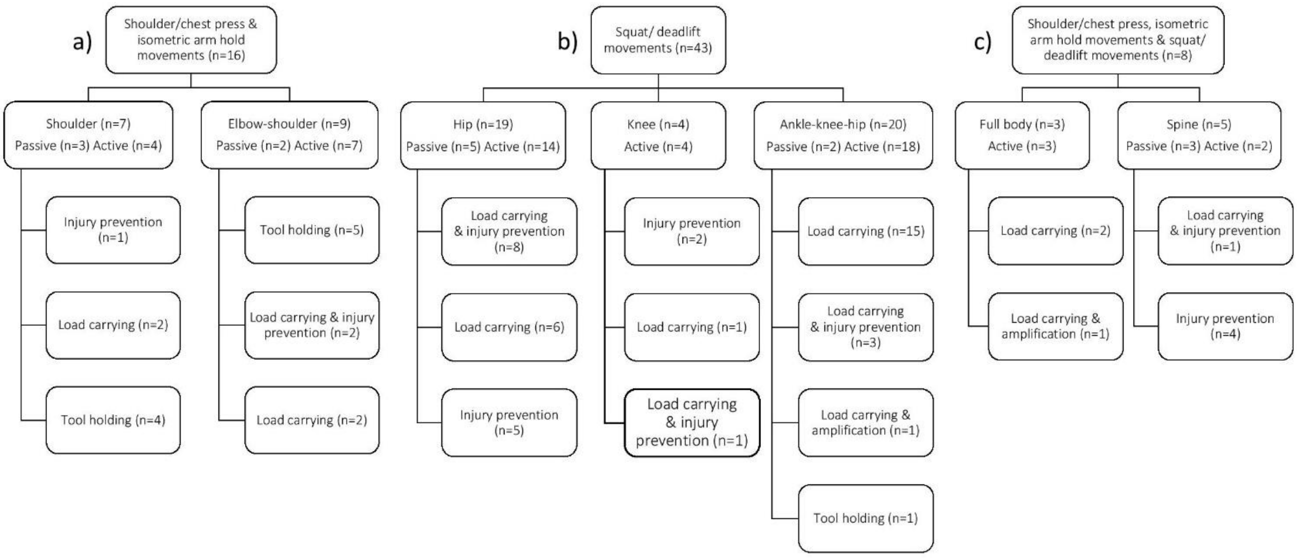

Figure 2 Breakdown of exoskeletons classified into their movement patterns, supporting joints and purpose. a) Shoulder/ chest press & isometric arm hold (Table 2) b) Squat/deadlift (Table 3) c) Shoulder/ chest press, isometric arm hold & squat/deadlift movements (Table 4).

4.1.3. Actuation system

Ninety percent of the included studies reported the actuation method used (Figure 2); these systems have been classified into four categories: electric (n=38), hydraulic (n=5), pneumatic (n=6) and passive (e.g. springs, pulleys, cables) (n=15). Seventy-eight percent of exoskeletons in this review were active, meaning they provide movement to the user through a mechatronic system and the creation of mechanical power through the use of actuators, while 22% were passive exoskeletons, meaning they used an exclusively mechanical system to provide support.

4.1.4. Task requirement

Task requirements were identified prior to exoskeleton design in 30% of the studies. These studies looked at kinematic modelling (n=10), gait analysis (n=5), or biomechanical analysis (n=5) to optimise their design for specific task requirements by quantifying the range of motion (ROM), DOF, joints supported, and additional torque provided.

4.1.5. Evaluation details

Human-exoskeleton integration analysis was the most prevalent form of evaluation with 68% of devices included in this review (Figure 3). Evaluations performed included biomechanical, physiological and psychophysical testing. Biomechanical evaluation was the most frequently used measure (n=39), followed by physiological evaluation (n=37) (Figure 3). Many studies used both physiological and biomechanical evaluations to indirectly evaluate device performance. Biomechanical testing captures the kinetics and kinematics of user's joint movement (Hamill & Knutzen, 2006), while physiological tests measure the user's energy cost (Gregorczyk, Hasselquist, Schiffman, Bensel, Obusek, & Gutekunst, 2010), and psychophysiological tests measure user's perception (subjective feedback) whilst using the exoskeleton (Mudie, Boynton, Karakolis, O'Donovan, Kanagaki, Crowell, Begg, LaFiandra, & Billing, 2018). Biomechanical evaluations vary and included motion capture (n=9), ground reaction forces (GRF) (n=2) and inertial measurement units (IMU) (n=6); physiological tests included electromyography (EMG) (n=32), while psychophysical tests included rate of perceived exertion and self-questionnaires (n=5). Only four studies measure performance using a direct method (time to completion).

All studies that tested muscle activation (recorded via EMG) reported reductions in some EMG signals (n=32). Such a reduction in EMG was considered a measure of how the exoskeleton reduced muscle work and thus the risk of injuries. Specific to the back, eight studies reported reductions of muscle activation of the erector spinae muscles between 15% and 54%; one study reported no changes, and one reported increased activation of the antagonist muscles.

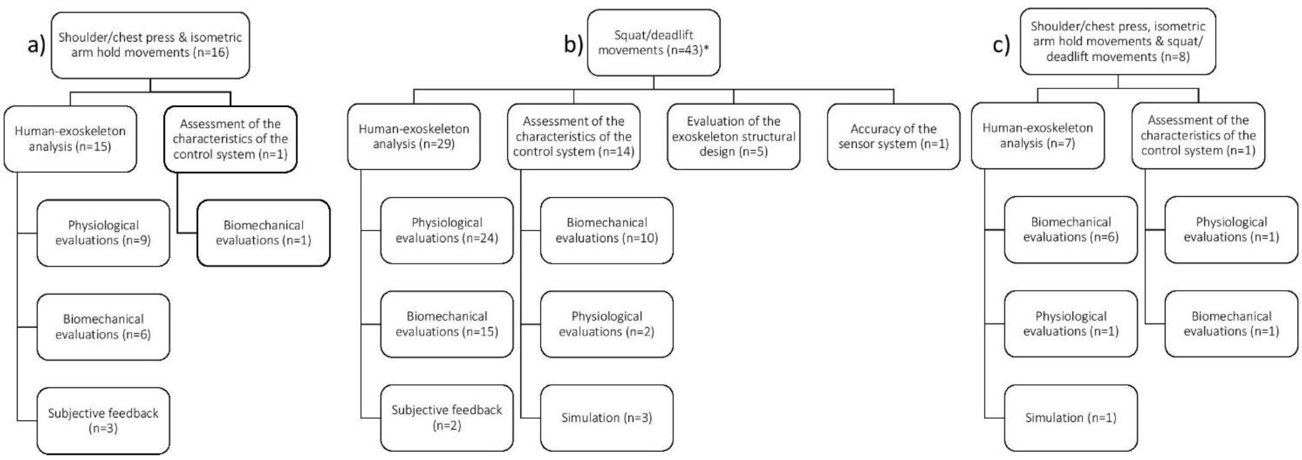

*Figure 3 Breakdown of exoskeletons classified into their movement patterns, testing performed and type of evaluation. a) Shoulder/ chest press & isometric arm hold (Table 2) b) Squat/deadlift (Table 3) c) Shoulder/ chest press, isometric arm hold & squat/deadlift movements (Table 4). * = Some studies have carried out multiple analysis.*

Due to the early stage of development for the majority of devices, participant sample sizes were relatively low (< 13). However, there were two studies (Baltrusch, van Dieën, van Bennekom, & Houdijk, 2018) and (Spada, Ghibaudo, Gilotta, Gastaldi, & Cavatorta, 2017) proposing commercially available exoskeletons (the Leavo (Table 3, Row 31) and Airframe (Table 2, Row 15)) that had larger participant cohorts with 18 and 29 participants respectively. The Airframe was also tested with a smaller cohort of 11 participants in a automotive factory environment performing controlled real-work tasks (Spada, Ghibaudo, Gilotta, Gastaldi, & Cavatorta, 2018), and the Daewoo Shipbuilding & Marine Engineering Hydraulics Wearable Robots (DSME-HWR) (Table 3, Row 20) performance was observed during in-field trials at a shipbuilding yard (Chu, Hong, Jeong, Kim, Kim, Jeong, & Choo, 2014).

Table 2 Exoskeleton classification for shoulder/chest-press and isometric arm hold

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
1	**Elbow – shoulder**	Exhauss Stronger	LC & IP	Arm – Lifting assist	P	Not reported	Not reported	9	Not applicable	Not applicable	Not reported	Not reported	Human-exoskeleton analysis	Lift, carry, place task. With & without exo condition. EMG, IMU, HR, RPE, CoP, time to complete.	8	4F (31 ± 2 years, 62 ± 10 kg, 166 ± 4 cm) 4M (33 ± 3 years, 78 ± 3 kg, 179 ± 3 cm)	Reduction of anterior deltoid muscle activity (54%) & stacking/unstacking (73%) tasks. No significant difference in back muscle activation. Increased antagonist muscle activity, postural strains, cardiovascular demand & changes in upper limb kinematics	(Theurel, Desbrosses, Roux, & Savescu, 2018)
2		Power assistive exoskeleton robot system for the human upper extremity	LC	Arm – Load assist	A	Not reported	8	Not reported	Human-robot cooperative control	Force sensors	Not reported	Not reported	Human-exoskeleton analysis	Holding a 10kg load. With & without exo conditions. EMG for elbow & shoulder flexion/ extension.	Not reported	Not reported	Reduction in EMG signals of the arms and shoulders while wearing the exoskeleton	(H. Lee, Lee, Kim, Gil, Han, & Han, 2012)
3		Stuttgart Exo-Jacket	TH	Arm - Stabilising	A	Electric (EM & HD)	12	Not reported	PID control	Hall sensors	Not reported	Biomechanical analysis - MoCap & IMU	Human-exoskeleton analysis	Subjective questionnaire on device comfort while performing flexion & extension.	3	Not reported	Not reported	(Ebrahimi, 2017; Ebrahimi, Groninger, Singer, & Schneider, 2017)
4		Iso-elastic upper limb exoskeleton	TH	Arm – Limb support	P	Passive (S)	Not reported	1.9	Not applicable	Not applicable	7.5	Not reported	Human-exoskeleton analysis	Using 4 weights and a spring balance, the effective lifting force at 7 different angles was measured	Not applicable	Not applicable	For higher loads there is a discrepancy between calculated and measured forces. Capable of supporting loads in the range of 40–120 N	(Altenburger, Scherly, & Stadler, 2016)
5		Under-actuated upper-body backdrivable	LC	Elbow – Load assist	A	Not reported	1	Not reported	Artificial neural network with a model-based intensity prediction	Myo-Armband	Not reported	Kinematics	Human-exoskeleton analysis	Varying torques in the 2 directions available	7	6 M and 1 F, (20 to 35 years)	RMS Error of 3.8 ± 0.8N at the end effector	(Treussart, Geffard, Vignais, & Marin, 2019)
6		4 DOF exoskeleton rehabilitation robot	LC & IP	Arm – Limb support	A	Cable-driven parallel mechanism	4	Not reported	IPC (Industrial Personal Computer)	Cable tension and encoder	Not reported	Kinematics	Characteristics of the control system	The exoskeleton drove robotic arm repetitively track the cubic polynomial trajectory	Not applicable	Not applicable	Trajectories tracking capability was demonstrated	(Wang, Li, Chen, & Zhang, 2019)

Table 2 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
7	**Elbow – shoulder**	Upper-limb exoskeleton	TH	Arm – Load assist	A	Electric (EM)	5	9.5	Not reported	Not reported	Not reported	Physiological	Human-exoskeleton analysis	Perform a movement of raising the arm with a drill above the head wearing or not the arm exoskeleton	10	8 M and 2 F, all right-handed, (28.8 ± 3.4 years, 173.3 ± 6.4 cm,72.32 ± 11.97 kg)	Exoskeleton reduces muscle activity	(Blanco, Catalán, Díez, García, Lobato, & García-Aril, 2019)
8		4-DOF upper-body exoskeleton	LC	Arm – Load assist	A	Not reported	4	Not reported	Admittance control & gravity compensation	Force Sensitive Resistor	Not reported	Biomechanics	Human-exoskeleton analysis	With the passive exoskeleton, in which three different payloads in the range of 0 kg to 5 kg were lifted	5	(20-30 years)	the developed method is able to estimate the load carrying status	(Islam & Bai, 2019)
9		Wearable upper arm exoskeleton	TH	Arm – Load assist	A	Electric (EM)	1	2	PD adaptive control	Not reported	4.5	Physiological	Human-exoskeleton analysis	Holding position with no weight, repeated with a 1.5, 3, 4.5kg load. With & without exo conditions. EMG for elbow & shoulder flexion/ extension.	5	(23-28 years, 168-183 cm)	The IEMG of every muscle is significantly decreased when the user wears the exoskeleton	(Yan, Yi, Du, Huang, Han, Zhang, Peng, & Wu, 2019)
11	**Shoulder**	PAEXO passive exoskeleton	TH	Shoulder – Joint support	P	Passive (S)	Not reported	Not reported	Not applicable	Not applicable	Not reported	Physiological	Human-exoskeleton analysis	T1: Screwing nuts continuously, and T2: Drilling using an electric drill (1.3 kg)	12	6 M and 6 F (24 ± 3 years, 176 ± 15 cm, 73 ± 15 kg)	The mean EMG amplitude of all evaluated muscles was significantly reduced when the exoskeleton was used. This was accompanied by a reduction in both heart rate and oxygen rate. The kinematic analysis revealed small changes in the joint positions during the tasks.	(Schmalz, Schändlinger, Schuler, Bornmann, Schirrmeister, Kannenberg, & Ernst, 2019)
12		Parallel-structured upper limb exoskeleton	LC	Arm – Load assist	A	Hypoid gear	2	12	Force-position hybrid	Angle sensors	Not reported	Kinematics	Human-exoskeleton analysis	Assisted by the exoskeleton, operator try to lift a 20kg load	1	Not reported	Structure can lift load up to 1.5 times of the exoskeleton's weight	(R. Zhang, Zhu, Li, Lin, & Zhao, 2019)
	(includes wrist)	ABLE exoskeleton	TH	Arm – Load assist	A	Not reported	7	Not reported	Force-position control	Not reported	Not reported	Not reported	Human-exoskeleton analysis	Biomechanical task analysis - tool holding above head with 5 shoulder compensation torques. With & without exo condition.	8	(24 ± 7 years, 63 ± 11 kg, 170 ± 5 cm) right-handed	Setting compensation to 1.935 kg.m led to disturbance of subjects' natural movements. Excluding Trial 5, strongest arm torques reduction occurs for Trial 3 (38.8%)	(Sylla, Bonnet, Colledani, & Fraisse, 2014; Sylla, Bonnet, Venture, Armande, & Fraisse, 2014)

Table 2 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
13		Shoulder exoskeleton	TH	Shoulder – Joint support	P	Passive (S)	Not reported	2	Not applicable	Not applicable	Not applicable	Physiological	Human-exoskeleton analysis	Repetitive lifting and placement work	5	(20-24 years)	Exoskeleton can reduce the muscle activity of shoulder muscle	(A. Zhu, Shen, Shen, Tu, Mao, Zhang, & Cao, 2019)
14	**Shoulder**	Hyundai Vest Exoskeleton (H-VEX)	TH	Arm – Limb support	P	Passive (S)	1	2.5	Not applicable	Not applicable	Not reported	Physiological	Human-exoskeleton analysis	Biomechanical task analysis - tool holding above head With & without exo conditions. High & low-task, with & without load.	10	(34.9 ± 3.96 years, 173.7 ± 6.20 cm, 72.1 ± 12.85 kg)	Assistive torque provided by H-VEX was shown to significantly decrease activation of the shoulder-related muscles during target tasks	(Hyun, Bae, Kim, Nam, & Lee, 2019)
15		Airframe	LC	Arm – Limb support	P	Not reported	Not reported	Not reported	Not applicable	Not applicable	Not reported	Not reported	Human-exoskeleton analysis	Static task - 3.5 kg on forearm. Repeated manual handling task - pick & place 3.4 kg. Precision task - tracing a continuous wavy line at shoulder height. Cognitive assessment -RPE. Time to complete. With & without exo condition.	29	M (51.5 ± 4.7 years, 81.6 ± 9.1 kg, 174.9 ± 2.3 cm)	Static = 31.1% relative longer time length with exo. Manual handling = Results are comparable. Precision = A significant 33.6% increase of the number of traced arches with exo.	(Spada et al., 2017, 2018)
														Controlled real work tasks: Mounting the clips of brake hoses underbody, sealing underbody using the sealing gun & mounting the seal on the rear door. With & without exo condition.	11	(177.2 ± 5.0 cm, 81.1 ± 7.3 kg, 45.8 ± 6.9 years)	Workers provided positive feedback for the exo as it helped to carry out tasks with less physical & mental effort. There was some potential interference of the exo during the mounting task.	(Spada et al., 2018)
16	**(includes hip)**	CANE	IP	Back – Joint support	A	Pneumatic (PnC)	Not reported	Not reported	Flow solenoid valve	IMUs	Not reported	Biomechanical task analysis - IMU	Human-exoskeleton analysis	Lift concrete blocks from the floor to 0.4m platform and return for 3 mins. With & without exo conditions. IMUs.	4	Not reported	A reduction in angle of waist bend by 32 degrees & shoulder twist by 17 degrees was seen while wearing the exo.	(Cho, Kim, Ma, & Ueda, 2018)

Note: Results interpreted by authors were 'Purpose', 'Task Analysis' and 'Testing Performed'.

Key:

PURPOSE: IP=injury prevention, LC= load carrying, TH= tool holding, Am= amplification.

ACTUATION METHOD: A= active, P= passive.

ACTUATORS: EM= electric motor, BoC= Bowden cable, AM= artificial muscle, PnC= pneumatic cylinder, LA= linear actuator, S= spring, HD= harmonic drive, HyC= hydraulic cylinder.

CONTROL METHOD: PI= proportional-integral, PD= proportional-derivative, PID= proportional-integral-derivative, EMG= electromyography.

SENSORS: FSR= force sensitive resistor, IMU= inertial measurement unit, EMG= electromyography.

EVALUATION DETAILS: exo= exoskeleton, ROM= range of motion, GRF= ground reaction force, EMG= electromyography, CoP= centre of pressure, CoG= centre of gravity, HR= heart rate, RPE= rate of perceived exertion, IMU= inertial measurement unit, M= male, F= female

Table 3 Exoskeleton classification for squat/deadlift

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details											**Evaluation Details**					
1	**Ankle – knee - hip**	Fortis	TH	Arm – Load transfer	P	Passive (S & counter-weight)	Not reported	Not reported	Not applicable	Not applicable	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	(Sokol, 2014)
2		HEXAR-CR50	LC	Leg – Load assist	A	Electric (EM & HD)	7	Not reported	PID control	Muscle volume sensor	30	Gait analysis for ROM, peak moments & peak power	Human-exoskeleton analysis	Walking at 3 km/h with 10 & 20 kg loads. With & without exo condition. EMG, GRF.	1	(29 years, 75 kg)	Reduction in leg muscle activations & GRF during 30 - 70% walking phases while wearing the exo.	(Lim, Kim, Lee, Kim, Shin, Park, Lee, & Han, 2015)
3		Lower extremity exoskeleton with power-augmenting purposes	LC	Leg – Walking assist	A	Electric (EM & HD)	14	Not reported	Swing control method	Absolute/ incremental encoders, strain-gauge sensor	Not reported	Not reported	Human-exoskeleton analysis	Left leg swings back & forward, EMG measured at the quad.	1	M (34 years)	Reduction in quad muscle activation	(Choi, Seo, Lee, Kim, & Kim, 2017)
4		Lower extremity exoskeleton	LC & Am	Leg – Walking assist	A	Hydraulic (HyC)	Not reported	30	PID & H∞ control	Encoders, force sensors	60	Kinematic modelling	Characteristics of the control system	Walking carrying 60 kg load. Squat with no load.	Not reported	Not reported	Walking bearing 60 kg load and squat action with no external load are realized effectively by this proposed control method	(Guo, Li, & Jiang, 2015; Guo, Zhang, & Jiang, 2016)
5		Servo controlled passive joint exoskeleton	LC	Leg – Load transfer	A	Electric (EM & ratchets)	8	6	Not reported	Force sensor	30	Not reported	Exoskeleton structural design	Finite element analysis for joint reaction forces & moments & resultant deformation of the structure during postural changes.	Not applicable	Not applicable	The ankle joint sees the largest amount of stress and deformation compared to the knee and hip.	(Naik, Unde, Darekar, & Ohol, 2018)
6		Lower-limb anthropo-morphic exoskeleton	LC & IP	Leg – Walking assist	A	Electric (EM)	8	Not reported	Impedance & supervisory control	Torque, position & GRF sensors	Not reported	Gait cycle	Human-exoskeleton analysis	Walking carrying 10 kg load for 10 m. With exo in passive mode, with exo in active mode & without exo conditions. EMG.	4	(25 ± 5 years, 77 ± 7 kg, 169 ± 2 cm)	An average reduction in muscle activity of 43.4% (Right Vastus intermedius) & 60.4% (Right Gastrocnemius) was seen when the exo was worn in active mode compared to no exo.	(Sado, Yap, Ghazilla, & Ahmad, 2018)
7		HIT-LEX	LC	Leg – Load assist	A	Electric (EM & S)	14	Not reported	PID control	In-Sole Sensing Shoe - Film pressure force sensors, strain sensor, angle sensors	Not reported	Gait cycle	Characteristics of the control system	Two experiments of foot lifting & landing & single leg stepping forward.	Not reported	Not reported	Exo could rapidly identify different working conditions & flexibly follow the swing leg movement.	(C. Zhang, Zang, Leng, Yu, Zhao, & Zhu, 2016; Y. Zhu, Zhang, Fan, Yu, & Zhao, 2016)

Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
8		Hydraulically Powered Exoskeletal Robot (HyPER)	LC	Leg – Load assist	A	Hydraulic (HyC)	10	Not reported	Not reported	Inclinometer, absolute encoders, insole sensor, FSRs	Not reported	Gait cycle for force transmission ratio	Characteristics of the control system	Stand-to-sit movement & walking experiment (0.83 m/s, 0 % grade, 10 min) with no load, 10, & 20 kg. GRF. With & without exo condition.	1	M (35 years, 75.1 kg, 176 cm)	In the standing position the GRF was not affected by a change in the payload & was reduced below wearers body weight in a semi-squat with exo.	(H. G. Kim, Lee, Jang, Park, & Han, 2015; J. W. Lee, Kim, Jang, & Park, 2015)
9		Lower Extremity Exoskeleton System	LC	Leg – Load assist	A	Hydraulic (HyC)	10	Not reported	PI control	Force sensors in - shoe, load cells	Not reported	Not reported	Exoskeleton structural design	Mechanical simulation in Matlab.	Not applicable	Not applicable	Not reported	(Sahin, Botsali, Kalyoncu, Tinkir, Onen, Yilmaz, Baykan, & Cakan, 2014; Sahin, Botsali, Kalyoncu, Tinkir, Onen, Yilmaz, & Cakan, 2014)
10		PRMI Exoskeleton	LC & IP	Leg – Walking assist	A	Electric (EM & HD	10	Not reported	Global fast terminal sliding mode & PD control	Encoders, inclinometers, foot pressure sensors	20	Kinematic modelling	Characteristics of the control system	Walking experiment (4.7 km/h) with a 20 kg load.	1	M (25 years, 61 kg, 175 cm)	The joint position tracking errors are maximum of 2◦ at the hip joint and 4◦ at the knee joint. These results confirm that the exoskeleton swing leg is able to shadow human motions in time by using the proposed controller.	(Ka, Hong, Toan, & Qiu, 2016)
11		Under-actuated lower extremity exoskeleton	LC	Leg – Load assist	A	Electric (EM, HD & springs)	6	Not reported	PID control	Muscle volume, insole sensors	Not reported	Not reported	Characteristics of the control system	Measure the effect of the exo on percentage maximum voluntary contraction via EMG. With & without exo condition.	Not reported	Not reported	Average decrease in %maximum voluntary isometric contraction of the leg muscles of 40.5% on level surface and 12.5% climbing stairs when wearing the exo.	(W. S. Kim, Lee, Lim, Han, & Han, 2013)
12		Lower extremity exoskeleton (LEE)	LC	Leg – Load assist	A	Electric (EMs & LA)	5	Not reported	Zero moment point control	Force sensors in foot pad	Not reported	Gait cycle for CoP	Characteristics of the control system	Walking test forward & backward.	Not reported	Not reported	The exoskeleton can walk stably with the user.	(Low, Liu, Goh, & Yu, 2006; Low, Liu, & Yu, 2005)

Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
13		HUALEX	LC	Leg – Load transfer	A	Electric (EM & HD)	10	15	Fuzzy-based variable impedance control	Encoders, IMUs, FSRs in foot pad	40	Kinematic modelling	Characteristics of the control system	Walking test with 30 kg load at speeds of 0.30m/s to 1.20m/s. Comparing the fuzzy-based variable impedance control to normal impedance control.	3	(70.83 kg)	The control fuzzy based impedance control strategy tracked human motion well and decreased interaction forces across all walking speeds compared to normal impedance control.	(Tran, Cheng, Rui, Lin, Duong, & Chen, 2016)
14		HUALEX	LC	Back – Load assist	A	Hydraulic (HyC)	7	Not reported	Hybrid Control combining zero-force control and zeroload control	tension and compression pressure sensor	25	Kinematic modelling	Comparison of control systems	Not reported	Not applicable	Not applicable	Hybrid control strategy can reduce interaction force between the pilot and the exoskeleton efficiently	(Q. Chen, Cheng, Shen, Huang, & Chen, 2019)
15	**Ankle – knee - hip**	Passive wearable moment restoring device	LC & IP	Back – Load assist	P	Passive (S & cables)	Not reported	Not reported	Not applicable	Not applicable	Not reported	Kinematic modelling	Human-exoskeleton analysis	Lift and lower loads (4.5 & 13.6 kg) twice. With & without exo conditions. Motion capture & EMG.	6	5M & 1F (27.7 ± 6.0 years, 67.7 ± 7.2 kg, 175 ± 0.06 cm)	With the device, back muscles demonstrated a 54% reduction in muscle activity and calculations suggested a reduction in maximum spine compressive forces by approximately 1300 N.	(Wehner, Rempel, & Kazerooni, 2010)
16		ExoHeaver	LC	Leg – Load assist	A	Electric (EM)	Not reported	26	Servo control	Not reported	15	Kinematic modelling	Exoskeleton structural design	Not reported	Not reported	Not reported	Not reported	(Yatsun & Jatsun, 2018)
17		Hip,knee, ankle exoskeleton	LC	Leg – Load assist	A	Electric (EM)	Not reported	Not reported	Super twisting sliding mode controller	Not reported	15	Simulation	Characteristics of the control system	Control of the transferring of the force to the Hip of a lower extremity exoskeleton while carrying weight	Not applicable	Not applicable	It provides better control over PID with uncertainties and disturbances	(Nair & Ezhilarasi, 2019)
18		Biomimetic lower limb exoskeleton (BioComEx)	LC	Leg – Walking assist	A	Variable stiffness actuator & SEA	Not reported	15	Closed-loop impedance control algorithm	Force sensors	Not reported	Biomechanical	Human-exoskeleton analysis	Not reported	1	Not reported	BioComEx is sufficiently satisfactory for walking applications	(Baser, Kizilhan, & Kilic, 2019)

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Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
19	**Ankle – knee - hip**	Wearable lower-body exoskeleton	LC	Leg – Limb support	A	Electric (EM)	6	11	Dual EKF sensor-less (user) joint torque estimation, LQG torque amplification control, and supervisory control	Joint angle potentiometers; and insole GRF sensors on each foot	Not reported	Biomechanical & physiological	Human-exoskeleton analysis	Lift a box weighing 4.3 kg from the floor, hold for a while, and then drop back on the floor, six consecutive times with and without assistance from the prototype exoskeleton suit	5	(28 ± 5 years, 178 ± 2 cm, 76 ± 5 kg)	Average recorded EMG signals taken at the right Vastus Inter-medius (Quadriceps) and right Gastrocnemius (calf muscles) of each participant revealed more than 36% reduction in muscle activity from the two-muscle groups	(Sado, Yap, Ghazilla, & Ahmad, 2019)
20		DSME-HWR	LC	Leg – Load assist	A	Electric (LA)	2	4.5	Compliance control algorithm - PD control	Not reported	Not reported	Biomechanical analysis – MoCap & GRF	Human-exoskeleton analysis	Knee joint optimisation. Original knee joint vs. optimised design for user exertion on exo with heavy load (30 kg). Force, joint angle & time to complete.	1	M	Original knee: Force = 392N, Time = 2.3s, Angular velocity = 60.9deg/s. Optimised design 1: Force = 43N, Time = 2.1s Angular velocity = 49.5deg/s. Optimised design 2: Force = 147N, Time = 2.0s, Angular velocity = 60 deg/s.	(Choo & Park, 2017a, 2017b; Chu et al., 2014; Jeong, Choo, Jeong, & Chu, 2014; H. G. Kim, Park, & Han, 2014)
21		Knee Assist Robotic Exoskeleton	IP	Leg – Walking assist	A	Electric (EM & S)	Not reported	Not reported	Torque control	Not reported	Not reported	Not reported	Characteristics of the control system	The participant walked & performed a sit-to-stand motion.	1	M (26 years, 85 kg, 171 cm)	The exo performed as expected for its 3 different control phases.	(Noh, Kwon, Yang, Oh, & Bae, 2016)
22	**Knee**	Soft knee exoskeleton	IP	Knee – Joint support	A	Electric (EM)	1	Not reported	Two-level configuration architecture for torque control	IMUs	Not reported	Biomechanics - Physiological	Human-exoskeleton analysis	15 squat cycles in six conditions (without wearing the exoskeleton, power-off exoskeleton, zero torque control, 10%, 30%, and 50% assistance	3	subject1: (25 years, 170 cm, 70 kg) subject 2: (32 years, 178cm) subject 3: (38 years, 175 cm, 85 kg)	The assistive control reduced the muscle effort of knee extensor	(S. Yu, Huang, Wang, Lynn, Sayd, Silivanov, Park, Tian, & Su, 2019)
23		Knee exoskeleton	LC & IP	Knee – Load assist	A	Electric (LA)	1	Not reported	Arduino UNO	EMG	Not reported	Biomechanics	Human-exoskeleton analysis	Two cycles of the knee flexion and extension	1	(63 kg, 160 cm)	The experimental and theoretical values of the joint angle and shank's angular velocities are validated for the kinematic design	(Jain, Himanshu, Bhupendra, Dharmendra, Aditya, Kumar, & Bera, 2019)

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Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
24	**Knee**	Exoskeleton intelligent portable system	LC	Knee – Load assist	A	Electric & Hydraulic (EM & HyC)	1	Not reported	Hydraulic pressure, PID control	Pressure sensor, encoder	30	Not reported	Characteristics of the control system simulation	Simulation of actual and expected knee angle and actuator location.	Not applicable	Not applicable	Control method can follow the natural motion of the knee.	(Li, Guo, Zhang, Zhou, & Zhang, 2012)
25	**Hip**	Muscle Suit	LC	Leg – Load assist	A	Pneumatic (AM)	Not reported	8.1	Switches	Not reported	Not reported	Not reported	Human-exoskeleton analysis	Hold load (20 kg) for 15 seconds for 3 trials. With & without exoskeleton condition. EMG.	10	Not reported	EMG values averaged across the 3 trials were reduced in the arms while wearing the exo.	(Muramatsu, Kobayashi, Sato, Jiaou, Hashimoto, & Kobayashi, 2011)
26		Lower-Back Robotic Exoskeleton	LC & IP	Back – Load assist	A	Electric (SEA & HD)	4	11.2	Admittance control & finite state machine	Encoder, IMUs, torque sensor, strain gauge	Not reported	Not reported	Human-exoskeleton analysis	Symmetrical loading (0, 5, 10, 15 & 25kg) & lift origin asymmetry (45°) (15 & 25kg) lifting & lowering task. With & without exo conditions. EMG.	1	M	The exo significantly reduces muscle activation of the back during symmetrical loading & for the lift origin asymmetry, larger muscle activations occurred with the device assisting the hips for flexion/extension & add/abduction.	(T. Zhang & Huang, 2018)
27		H-WEX	LC & IP	Back – Joint support	A	Electric (EM, HD & Pulley)	8	4.5	Motion & torque control	Hall sensor, IMU	15	Not reported	Human-exoskeleton analysis	Pick 15kg load from ground to pelvic height. Squat & stoop posture conditions. With & without exo conditions. EMG for hip flexion/ extension.	9	M (33.4 ± 2.4 years, 73.0 ± 9.0 kg, 173.2 ± 4.5 cm)	Decrease in muscle activity of the muscles related to waist motions (back and abdominals) of between 10-30% while wearing the exo.	(Ko, Lee, Koo, Lee, & Hyun, 2018)
28		APO	LC & IP	Back – Load assist	A	Electric (EM, SEA)	4	Not reported	Lift detection	Encoders, IMUs	Not reported	Not reported	Characteristics of the control system	2 sessions for training lift detection algorithm, using 3 initial positions & 3 lifting techniques for 5 kg box. 1 session for testing algorithm. EMG, IMU.	7	M (27.9 ± 2.3 years, 70 ± 6.4 kg, 178.1 ± 8.1 cm)	Accuracy of 97.48 ± 1.53% was achieved for lift detection with a time delay of <160ms. EMG showed at least 30% reduction in back muscle activation when the exo provided torque.	(B. Chen, Grazi, Lanotte, Vitiello, & Crea, 2018; Lanotte, Grazi, Chen, Vitiello, & Crea, 2018)
												Not reported	Human-exoskeleton analysis	Walking on treadmill, varied speeds and level of exo assistance. With & without exo conditions. Hip joint angle, torque & motion capture.	5	(29.2 ± 6.3 years, 74.4 ± 6.8 kg, 173 ± 7 cm)	Negligible interference of the exo in human kinematics. Small displacements in the exo-human interaction points.	(D'Elia, Vanetti, Cempini, Pasquini, Parri, Rabuffetti, Ferrarin, Molino Lova, & Vitiello, 2017)

Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
29	**Hip**	Robo-Mate - Mk2	LC & IP	Back – Load assist	A	Electric (Parallel elastic actuator - EM, HD)	1	Not reported	PD & Torque control	Torque sensor	15	Not reported	Characteristics of the control system simulation	Evaluating the differences in the torque control transparency when used with the parallel elastic actuator and the actuator without parallel elasticity.	Not applicable	Not applicable	Significant improvements in torque-control performance, thus encouraging the use of parallel-spring arrangements	(Toxiri, Calanca, Ortiz, Fiorini, & Caldwell, 2018)
												Not reported	Human-exoskeleton analysis	Pick & place loads (7.5 kg ,15 kg). With & without exo conditions. EMG, interface pressure, perceived comfort & usability.	12	M (27 ± 2 years, 75.38 ± 10.1 kg, 179.4 ± 0.65 cm)	Reduced muscle activity of the Erector Spinae (12%-15%) & Biceps Femoris (5%).	(Huysamen, de Looze, Bosch, Ortiz, Toxiri, & O'Sullivan, 2018)
												Not reported	Accuracy of the sensor system	Compare 3 strategies for input into controller to follow user intention. IMU, EMG & finger pressure sensor. Lift & lower load (2 x no load, 5 & 10kg) for each strategy.	13	11M & 2F (28.9 ± 4.3 years, 69.8 ± 10.6 kg, 178 ± 6.6 cm)	The IMU strategy generated a reference signal that shows little dependence on load, by contrast, the EMG & finger pressure strategies show a stronger relationship.	(Toxiri, Koopman, Lazzaroni, Ortiz, Power, de Looze, O'Sullivan, & Caldwell, 2018)
								11				Biomechanics - Physiology	Human-exoskeleton analysis	Lifting task with three different techniques; FREE, SQUAT and STOOP, once with NO EXO and three times with the EXO (INCLINATION, EMG &HYBRID)	10	25.0 ± 6.9 years, 70.9 ± 8.8 kg,1.77 ± 0.06 m	Compression forces with the EXO were substantially lower compared to NO EXO. However, no single EXO control mode was superior over the others due to performance limitations of the actuators	(Koopman, Toxiri, Power, Kingma, van Dieën, Ortiz, & de Looze, 2019)
												Kinematic modelling	Characteristics of the control system	Walking, standing and bending	1	Not reported	Study shows that it is possible to perform reliable online classification	(Poliero, Toxiri, Anastasi, Monica, Caldwell, & Ortiz, 2019)
30		Stand-alone powered exoskeleton robot suit	LC	Back – Load assist	A	Electric (EM, HD)	Not reported	8	Not reported	Encoders	Not reported	Biomechanical analysis	Human-exoskeleton analysis	Flexion/extension of trunk with load (33 kg). Torque, time to complete	Not reported	Not reported	The motion was completed in 0.7 seconds with load, where this is 0.49 seconds longer than that of the no-load condition.	(H. Yu, Choi, Han, Choi, Chung, & Suh, 2015)

Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										Evaluation Details						
31	Hip	Laevo	IP	Back – Joint support	P	Passive (S)	Not reported	Not reported	Not applicable	Not applicable	Not reported	Not reported	Human-exoskeleton analysis	Objective & subjective measures for 12 functional tasks.	18	M (27.7 ± 5.1 years, 74.7 ± 8.0 kg, 178 ± 6 cm)	Decreased the local discomfort in the back in static holding tasks and at the dorsal side of the upper legs in static forward bending. Showed adverse effects on tasks that require large ROM of trunk or hip flexion including walking.	(Baltrusch et al., 2018)
												Physiology	Human-exoskeleton analysis	Lift and lower a 10-kg box (0.39 0.37 0.11 m, with 2.5 cm diameter handles) at a rate of 6 lifts per minute (for 5min)	13	28.9 years (4.4), 1.80 m (0.04) m and 76.9 kg (12.0)	Wearing the exoskeleton during lifting, metabolic costs decreased as much as 17%. In conjunction, participants tended to move through a smaller range of motion, reducing mechanical work generation	(Baltrusch, van Dieën, Bruijn, Koopman, van Bennekom, & Houdijk, 2019)
32		Laevo V2.4	IP	Back – Joint support	P	Passive (S)	Not reported	Not reported	Not reported	Not reported	Not reported	Biomechanics - Physiology	Human-exoskeleton analysis	Motion and surface EMG were measured during two consecutive periods of at least 30 min, one with and one without the exoskeleton	10	mean age and BMI of the participants was respectively 45.6 (SD 11,64) and 26.9 (SD 2,78)	RMS values were significantly higher for the Trapezius muscle with the exoskeleton (Mdn = 44.02) compared to the measuring period without the device (Mdn = 34.83, T = 0, p < 0.05, r = −.73); No differences were found for Erector Spinae and Biceps Femoris muscle activity. Participants reported significantly higher discomfort scores for the upper back/chest and thigh region with the exoskeleton (both p < 0.05, r = −.68).	(Amandels, het Eyndt, Daenen, & Hermans, 2019)
33		Robo-Mate exoskeleton	LC & IP	Back – Load assist	A	Electric (Parallel elastic actuator - EM, HD)	Not reported	Not reported	Not reported	Not reported	15	Biomechanical analysis – MoCap, EMG & GRF	Exoskeleton structural design	Simulation of lifting and lowering tasks with exo to test actuator performance.	Not applicable	Not reported	The results show the improvement in weight, peak torque and peak power by 20%, 50% and 40% respectively as compared with the current prototype	(Masood, Ortiz, Fernandez, Mateos, & Caldwell, 2016)
									Acceleration-based torque control	Trunk angular acceleration	Not reported	Physiology	Human-exoskeleton analysis	Lifting and the lowering of an external weight of 5kg and 10kg, repeated at three different speed: fast, normal and slow	7	Not reported	The data on peak muscular activity at the spine show promising trends	(Lazzaroni, Toxiri, Caldwell, Anastasi, Monica, Momi, & Ortiz, 2019)

Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
34		Hip-type exoskeleton	LC & IP	Back – Load assist	A	Electric (EM)	1	Not reported	Not applicable	Sensorless force estimator	Not reported	Physiological	Human-exoskeleton analysis	Lift load from 0 to 25 kg (5kg increments) load from the ground. With & without exo condition. EMG.	10	Average age 30 years, height 176 cm & weight 75 kg	EMG value was significantly lower when the exoskeleton on in all loading conditions	(Xia, Feng, Zheng, Wang, & Wu, 2019)
35		Spine exoskeleton	LC	Back – Joint support	A	Electric (EM)	9	Not reported	Torque control	Torque sensor	Not reported	Biomechanics - Physiology	Human-exoskeleton analysis	Repetitive, stoop-lift of a 10kg box at different speeds	5	(21 – 36 years, 60 – 82.12 kg, 170 – 182 cm)	All cost functions reduced significantly the human torque loads. However, they result in different amounts and distributions of the load reduction as well as different contributions from the passive and active components of the exoskeleton	(Harant, Millard, Sarabon, & Mombaur, 2019)
36	**Hip**	VT-Lowe's exoskeleton	LC	Back – Load transfer	P	Passive (Flexible beams)	Not reported	Not reported	Not reported	Not reported	Not reported	Physiology	Human-exoskeleton analysis	Stoop, squat and freestyle lifting trials performed in the sagittal plane, plus lift origin asymmetry (60°) for 0% and 20% of subject bodyweights, both with and without exoskeleton	12	22.75 (4.35) years, 178.92 (6.05) cm, 80.41 (5.59) kg and 25.16 (1.91) kg/m2	Results demonstrated that the exoskeleton could reduce the average peak and mean muscle activation of back and leg muscles regardless of different levels of box weights and lifting types.	(Alemi, Geissinger, Simon, Chang, & Asbeck, 2019)
37		Booster exoskeleton	IP	Back – Joint support	P	Springs	Not reported	Not reported	Not applicable	Not applicable	Not reported	Physiology	Human-exoskeleton analysis	Carry and lift the object weighing 9.5 kg	3	Not reported	With wearing the exoskeleton, the subjects' breathing, and heart rate were significantly reduced	(Han, Li, Wang, Ma, & Ai, 2019)
38		Back assistance exoskeleton	LC	Back – Joint support	A	Pneumatic artificial muscle	Not reported	7.6	Not reported	Not reported	18	Physiology	Human-exoskeleton analysis	Romanian deadlift motion of lifting 15 kg repeated 10 times at a time, totalling 5 times	1	Not reported	Decreased level of 20% to 30% in muscle activation when lifting the loads with exo	(Shin, Park, Lee, Lee, & Kim, 2019)
39		Wearable waist exoskeleton	IP	Back – Joint support	A	Electric (EM)	1	5	Torque control	Angle, angular velocity and current	Not reported	Physiology	Human-exoskeleton analysis	Symmetrical lifting for six different objects (0, 5, 10, 15, 20, 25 kg) under two conditions of with and without the exoskeleton	10	average age 26 years, weight 70 kg, and height 174 cm	The exoskeleton significantly reduced the back muscular activity during repetitive lifting tasks	(Yong, Yan, Wang, Wang, Li, & Wu, 2019)

Table 3 continued…

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
40	**Hip**	HAL	IP	Back – Joint support	A	Not reported	1	Not reported	EMG based control	Triaxial accelerometer and potentiometers	Not reported	Physiology	Human-exoskeleton analysis	2 sessions (one with HAL and one without HAL) of stoop lifting/placing, until they feel they cannot continue. In each session, subjects were asked to lift and place a small box, (for males, 12 kg, for females, 6 kg).	20	13 M, 7 F (31.5 ± 6.6 years)	Muscle coordination changes were dominated by changes in timing coefficients, with minimal change in muscle synergy vectors	(Tan, Kadone, Miura, Abe, Koda, Yamazaki, Sankai, & Suzuki, 2019)
41		SJTU-EX	LC	Back – Load assist	A	Electric (EM)	8	Not reported	Not reported	Not reported	Not reported	Not reported	Exoskeleton structural design	Walking simulations	Not applicable	Not reported	Not reported	(Miao, Gao, & Pan, 2015)
42		Wearable Exoskeleton Power Assist System	LC & IP	Back – Load assist	A	Electric (EM)	1	11	User intention via EMG	EMG	Not reported	Kinematic modelling	Human-exoskeleton analysis	Lift and lower load 20 kg load from/to ground. With & without exo condition. EMG.	Not reported	Not reported	Muscle activation of the thigh muscles was reduced when wearing the device.	(Naruse, Kawai, Yokoi, & Kakazu, 2003)
43		SPEXOR	LC & IP	Back – Joint support	P	Passive (Flexible beams)	4	Not reported	Not applicable	Not applicable	Not reported	Not reported	Human-exoskeleton analysis	ROM testing, trunk flexion/ extension, lateral bending & rotation. 4 exo configuration conditions. Motion capture.	3	M (30 years, 66 kg, 171.5 cm)	Using flexible beams as a back interface increases the trunk range of motion by more than 25% compared to its rigid counterpart. With the flexible beams, the range of motion is only decreased by 10% compared to not wearing an exo.	(Näf, Koopman, Baltrusch, Rodriguez-Guerrero, Vanderborght, & Lefeber, 2018)

Note: Results interpreted by authors were 'Purpose', 'Task Analysis' and 'Testing Performed'.
Key:
PURPOSE: IP=injury prevention, LC= load carrying, TH= tool holding, Am= amplification.
ACTUATION METHOD: A= active, P= passive.
ACTUATORS: EM= electric motor, BoC= Bowden cable, AM= artificial muscle, PnC= pneumatic cylinder, LA= linear actuator, S= spring, HD= harmonic drive, HyC= hydraulic cylinder.
CONTROL METHOD: PI= proportional-integral, PD= proportional-derivative, PID= proportional-integral-derivative, EMG= electromyography.
SENSORS: FSR= force sensitive resistor, IMU= inertial measurement unit, EMG= electromyography.
EVALUATION DETAILS: exo= exoskeleton, ROM= range of motion, GRF= ground reaction force, EMG= electromyography, CoP= centre of pressure, CoG= centre of gravity, HR= heart rate, RPE= rate of perceived exertion, IMU= inertial measurement unit, M= male, F= female

Table 4 Exoskeleton classification for shoulder/chest-press, isometric arm hold and squat/ deadlift

Row	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										Evaluation Details						
1	Spine	Passive spine exoskeleton	IP	Back – Joint support	P	Passive (S & pulley)	1	Not reported	Not applicable	Not applicable	Not reported	Kinematic modelling	Human-exoskeleton analysis	Dynamic - flexion/extension for 120 s with a constant speed. Static - hold 3 flexion positions (small, medium, & full-range) for up to 120 s. EMG, IMU. With & without exo condition.	3	M (26.7 ± 3.3 years, 68.3± 6.7 kg, 172 ± 12 cm)	EMG reduction at lumbar (24%) & thoracic (54%) level with exo & a reduction of intervertebral bending moment (36N.m) & muscle force (479N).	(H. Zhang, Kadrolkar, & Sup, 2016)
2		Spine-inspired continuum soft exoskeleton	IP	Back – Joint support	A	BoC	3 for each disc	Not reported	Virtual impedance model	Load cell	Not reported	Biomechanics	Human-exoskeleton analysis simulation	Stoop lifting of 15 kg with 10 repetitions	3	Not reported	Able to successfully track the desired force with high accuracy.	(Yang, Huang, Hu, Yu, Zhang, Zhou, Carriero, Yue, & Su, 2019)
3		FLx	IP	Back – Joint support	P	Passive	Not reported	1.08	Not reported	Not applicable	Not applicable	Biomechanics	Human-exoskeleton analysis simulation	A 3 × 3 x 2 × 2 repeated measures design was employed in this study, in which all combinations of intervention (FLx exo, V22 exo, none), lift origin height (shin, knee, waist), lift origin asymmetry (0° & 45°), & load weight (9.07 kg & 18.14 kg) were evaluated	10	(24.9 ± 5.0 years, 81.1 ± 16.1 kg, 179.4 ± 4.6 cm)	FLx reduced peak torso flexion at the shin lift origin, but differences in moment arms or spinal loads attributable to either of the interventions were not observed. Thus, industrial exoskeletons designed to control posture may not be beneficial in reducing biomechanical loads on the lumbar spine.	(Picchiotti, Weston, Knapik, Dufour, & Marras, 2019)
4		V22	IP	Back – Joint support	P	Passive	Not reported	1.29	Effectors worn on the hand	Not applicable	68							
5		Exoskeleton for the back	LC & IP	Back – Joint support	A	Pneumatic (PnC)	Not reported	Not reported	User intention	EMG	25	Biomechanical simulation	Human-exoskeleton analysis simulation	Measure of forces to the back based on a human-machine model.	Not applicable	Not applicable	A decrease of the forces by 35% on the L5-S1 joint & by 43% on the back muscles can be noted at the beginning of the lift.	(Durante, Antonelli, & Zobel, 2018)
6	Full Body	Robot Suit HAL	LC	Back – Load assist	A	Electric (EM & HD)	14	Not reported	Torque control based on EMG	EMG, potentiometers, IMUs, ground reaction force sensors	50	Kinematic modelling	Characteristics of the control system	Measure joint angles and bio-signals while holding load (50 kg).	1	M (26 years)	The designed locking mechanism included in the power units kept the angles of the upper limbs steady while the user held the load, and the physical burden on the upper limbs of the user was reduced.	(Satoh, Kawabata, & Sankai, 2009)

Table 4 continued…

	Supported Joint	Device Name	Purpose	Targeted Assistance	Actuation Method	Actuators	DOF	Weight (kg)	Control	Sensors	Load Capability (kg)	Task Analysis	Testing performed	Test details	Sample size	Participant details	Results	Ref.
		Operational Details										**Evaluation Details**						
7	**Full Body**	UTRCEXO	LC	Leg – Walking assist	A	Electric (EM & HD)	8	Not reported	Position & torque control. Walking intention	encoders, FSRs, force/torque sensor	Not reported	Gait analysis for GRF & motion capture	Human-exoskeleton analysis	Walking with 10 kg weight.	1	(73 kg, 176 cm)	Detects step initiation using the insole type FSRs prior to movement. Allows the operator to easily walk with a 10 kg load. Does not take the operator's desired step velocity into account.	(Cha, Oh, Lee, Kim, Kim, & Kim, 2015)
8	**Full Body**	Body Extender (BE)	LC & Am	Full body – Load assist	A	Electric (EM)	22	160	User triggered motion	Encoders, accelerometer, force/torque sensors	50	Not reported	Human-exoskeleton analysis	Assess the tracking (with and without load) and the grasping/ lifting/ handling (up to the rated load) capabilities of the device.	Not reported	Not reported	Maximum resistance forces of 30 N are well tolerated by the user, good mass distribution of the device, walking phase somewhat unnatural. At max rated load the system equilibrium becomes unstable	(Marcheschi, Salsedo, Fontana, & Bergamasco, 2011)

Note: Results interpreted by authors were 'Purpose', 'Task Analysis' and 'Testing Performed'.
Key:
PURPOSE: IP=injury prevention, LC= load carrying, TH= tool holding, Am= amplification.
ACTUATION METHOD: A= active, P= passive.
ACTUATORS: EM= electric motor, BoC= Bowden cable, AM= artificial muscle, PnC= pneumatic cylinder, LA= linear actuator, S= spring, HD= harmonic drive, HyC= hydraulic cylinder.
CONTROL METHOD: PI= proportional-integral, PD= proportional-derivative, PID= proportional-integral-derivative, EMG= electromyography.
SENSORS: FSR= force sensitive resistor, IMU= inertial measurement unit, EMG= electromyography.
EVALUATION DETAILS: exo= exoskeleton, ROM= range of motion, GRF= ground reaction force, EMG= electromyography, CoP= centre of pressure, CoG= centre of gravity, HR= heart rate, RPE= rate of perceived exertion, IMU= inertial measurement unit, M= male, F= female

5. Discussion

The aim of this review was to analyse the current literature to identify characteristics of industrial exoskeletons that can be useful to military manual handling tasks. The high percentage of exoskeletons targeting load carrying reflects the industry need for devices that can support manual handling workers by preventing injuries and improving productivity. Therefore, the application of these exoskeletons to Australian Defence Force personnel performing manual handling could help reduce the substantial personal and financial cost of injuries.

Most of the exoskeletons included in this review are in early development and are designed to support manual handling via a number of methods, such as providing assistive torque to enhance the ability of joints to carry external loads (e.g., Huysamen et al., 2018 (Table 3, Row 29); Ko et al., 2018 (Table 3, Row 27); Theurel et al., 2018 (Table 2, Row 1); T. Zhang et al., 2018 (Table 3, Row 26)), providing loading pathways that bypass the user's joints (e.g., Sado et al., 2018 (Table 3, Row 6)) and/or providing support or limiting the joint movement to prevent harmful motions (e.g., H. Zhang et al., 2016 (Table 4, Row 1)).

There were a large number of squat/deadlift (lower limb) exoskeleton devices (56%) with 27% of devices supporting the ankle, knee and hip joint and 26% solely supporting the hip. 95% of the hip supported devices aim to assist the lower back (e.g., B. Chen et al., 2018 (Table 3, Row 28); H. Yu et al., 2015 (Table 3, Row 30); T. Zhang et al., 2018 (Table 3, Row 26)). This could be due to the prevalence of lower back injuries and their correlation to lifting from the ground (Karwowski, Jang, Rodrick, Quesada, & Cronin, 2005) and hyperflexion of the lumbar spine (Kudo, Yamada, & Ito, 2019), which is controlled by the hip joint (categorised as a part of the squat/deadlift systems). Exoskeletons assisting the back actuate from the hip to minimize the increased torques to the lower back caused by hyper flexion during lifting. However, since spine motion has multiple DOF (Wilke, Kienle, Maile, Rasche, & Berger-Roscher, 2016), exoskeletons actuating from the hip on a single plane (1 DOF, i.e. flexion/extension) may result in movement restriction where physiological rotation and lateral bending of the spine are impeded resulting in increased effort (Bellini, Galbusera, Raimondi, Mineo, & Brayda-Bruno, 2007) or reduced performance (Burgess, Hillier, Keogh, Kollmitzer, & Oddsson, 2009; S. J. Ferguson & Steffen, 2005).

Task analysis prior to the design of an exoskeleton could be beneficial for better support of manual handling tasks. Thirty percent of studies in this review reported performing a priori task analysis. Through this analysis the operational complexity of the exoskeleton (type of actuation, DOF, the control system and the method of power transmission) could be optimised for specific tasks. For instance, with biomechanical analysis of the task, it is possible to identify which joints undergo high moments and which ones are allowed free movement (e.g., H. Yu et al., 2015 (Table 3, Row 30)); this informs the choice of how many DOF should be allowed at a joint for that task, as well as how much support should be provided. As active actuators can face issues such as big size, heavy weight, bulkiness, inefficient force transmission, low speed and inaccurate control (Popov, Gaponov, & Ryu, 2017; Zaroug et al., 2019), the power-to-weight ratio should be optimized in order to provide the minimum assistance needed to support the specific joint for the requirements of the task (e.g., Masood et al., 2016 (Table 3, Row 33)) and to replace some actively actuated joints with passive actuators where appropriate (e.g., Chu et al., 2014 (Table 3, Row 20); Ebrahimi, 2017 (Table 2, Row 3)). Optimisation could therefore lead to a reduction in weight, inertia, friction, and complexity of the exoskeleton while increasing its efficiency, thus allowing for lower impedance (interaction force between the exoskeleton and the user) and better control.

Although the majority of studies indicated that exoskeletons could reduce muscle activation, evidence was not conclusive with studies reporting an increase in muscle activations of the antagonist muscles (Theurel et al., 2018) (Table 2, Row 1). Therefore, EMG signals should be recorded from antagonist muscles, as well as from those muscles acting at joints other than the one supported by the exoskeleton (Weston, Alizadeh, Knapik, Wang, & Marras, 2018). Although methodologically challenging, the concomitant use of EMG on agonist and antagonist muscles will provide a measure of exoskeleton interference with pattern of muscle activation which are essential for proper movement coordination and low energy cost (Lay, Sparrow, Hughes, & O'Dwyer, 2002; Tan et al., 2019; Wakeling, Blake, & Chan, 2010).

Control strategies also play a large part in the optimisation of an exoskeleton system. Exoskeleton designers in this review tested the exoskeleton control strategies for (1) their ability to follow the user's joint motions, (2) exoskeleton stability, and (3) load reduction for the duration of the task. A few exoskeleton systems looked into user intention (e.g., Durante et al., 2018 (Table 4, Row 5)) and task recognition (e.g., B. Chen et al., 2018 (Table 3, Row 28)) control strategies. These strategies could provide the information needed to develop smooth motion and predictive human-intention algorithms, creating smarter, more efficient exoskeleton systems. With the development of predictive algorithms there is the ability to provide assist-as-needed control, reducing power consumption and preserving the musculoskeletal capacity of the user.

Findings from this review demonstrated there were no consistent methodologies used to evaluate exoskeletons for manual handling. Further development of current exoskeleton testing and reporting standards (e.g. Mudie et al., 2018) to include military manual handling tasks (e.g. ASTM F48 committee on exoskeletons and exosuits) is critical to enable valid and reliable comparisons between future devices. However, it is worth noting that none of the included studies were of a prospective nature and only performed analysis at a single time point. Prospective studies (and the accompaying standards) could be beneficial to validate the use of exoskeletons for injury prevention or augmentation.

5.1. Military manual handling considerations

While the tasks performed by military personnel may be similar to those performed in industry, there are additional considerations for the use of exoskeletons in a military workplace. For instance, in-field surfaces can be uneven and loose, requiring exoskeletons to be robust and flexible to compensate for unexpected perturbations. Military manual handling exoskeletons could also face a range of weather conditions, confined spaces where the device's dimensions could be restrictive, limited access to power supply, large amounts of dust and dirt, and rough use, necessitating a durable and efficient exoskeleton design. Additionally, the necessity to integrate the device into military personnel's uniform or body armour should be considered.

Devices developed for load carriage, amplification or injury prevention could assist with minimising the risk of injury from carrying large loads and performing repetitive complex movements from the ground, as often performed by military personnel (Sharp, Rosenberger, & Knapik, 2006). The loading required for military manual handling tasks is heavier than what would be required of personnel in many other industries (Forde & Buchholz, 2004; Roja, Kalkis, Reinholds, & Roja, 2016). For instance, in a military context lift-to-platform tasks (shoulder/chest-press movement) require loads of 25.6 ± 8.5 kg to be lifted while lift-carry-lower tasks (isometric arm hold movement) require loads of 31.1 ± 17.1 kg to be carried distances of 127.8 ± 126.2 m (Carstairs et al., 2018). In comparison, in an industry context, e.g., in large international airports, the weight of baggage handled by security personnel ranges between 10 and 23 kg (Gebhardt, 2019). This highlights the fact that workplace context can affect the demand of the job, thus the different need for assistance.

The findings from this review did not highlight whether current active or passive exoskeleton would be capable of sustaining the loads required by military personnel (Table 2-4). It was unclear whether the reported load capability referred to the load limits of the exoskeleton structure and/or actuators, the load limit that the user could support, or the maximum loads required by the task in industry. Additionally, lift-carry-lower tasks are mostly unilateral (load only on one side of the body) (74%) (Carstairs et al., 2018) and require asymmetrical muscle activation in the spine to maintain stability due to an increase in internal torsional forces. This review found no studies that tested unilateral loading. However, three exoskeleton devices in this review were tested for lift origin asymmetry (the lift starts at an angle away from the sagittal plane), which could also causes asymmetrical muscle activations, and found that this decreased muscle activation of the ipsilateral muscles while wearing the exoskeleton (Alemi et al., 2019 (Table 3, Row 36); Picchiotti et al., 2019

(Table 4, Row 3); T. Zhang et al., 2018 (Table 3, Row 26)). It would therefore be beneficial for an exoskeleton to actively compensate for unilateral loads and lift origin asymmetry.

6. Conclusion

The large portion of devices targeting load carrying reflects the industry and military need for devices that can support manual handling workers with the aim of preventing injuries and improving productivity. The joint requirements for the two most common tasks in military manual handling are well represented in current state of exoskeleton systems. The unique considerations of the military such as heavy external loads, load asymmetry, harsh environments and uniform integration mean that an adaption of current technology or a military specific design would be required for introduction into the Australian Defence Force.

7. Key points

- Although this field is fast growing, the majority of the included exoskeletons were in an early stage of development.
- Determining exoskeleton design challenges through task analysis could be useful for understanding how to better support military manual handling tasks.
- It would be beneficial for an exoskeleton to actively compensate for unilateral external loads due to their prevalence in military manual handling tasks.
- It was unclear whether current active exoskeleton would be capable of sustaining the loads required by military personnel.
- Adaption of current technology would be required for the introduction of exoskeletons into a military setting.

8. Limitations

Only Scopus was used as the citation database for this review and while it is extensive in the literature it lists, important studies on current exoskeletons may not have been included. We also acknowledge that by searching for research studies, we omit some of the most widely used commercially available exoskeletons for which there aren't any published research. Additionally, some of the data included in the tables was interpreted by the authors of this review rather than stated in the reviewed study. The search terms used were based on the definition of manual handling tasks by researchers of Australian Army tasks and may not be inclusive of all manual handling industries. The review applied a broad range of exoskeletons to two specific tasks (lift to platform and lift-carry-lower), the exoskeletons in the review were not always intended for these tasks. Furthermore, the review did not include exoskeletons that carried loads posterior to the user, it is possible that these devices could be adapted for these tasks. This review did not explore other systems that could be useful to military manual handling personnel such as smart sensor systems.

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